1274251

PATENT SPECIFICATION

(11) 1274251

DRAWINGS ATTACHED

(21) Application No. 23789/69 (22) Filed 9 May 1969

(31) Convention Application No. 1841 (32) Filed 9 May 1968

(31) Convention Application No. 1843 (32) Filed 9 May 1968 in

(33) Hungary (HU)

(45) Complete Specification published 17 May 1972

(51) International Classification G01S 9/62

(52) Index at acceptance
H4D 747 749 772 773 782 783
C2J 32

(54) A DEVICE FOR MEASURING DISTANCE

(71) We, MAGYAR OPTIKAI MÜVEK, of Csörsz utca 35/43, Budapest XII, Hungary, a Hungarian Body Corporate, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

THIS INVENTION relates to a method of and a device for measuring distance by measuring the phase differences of modulated light.

Known electro-optical distance measuring devices have a number of defects. These originate mainly from the faults of light-modulators, from complicated and tedious measurement and evaluation methods, from difficulties in attaining higher ranges, from large dimensions, and excessive weight and power consumption if long range and high accuracy are required.

According to one aspect of the invention there is provided a method of measuring a distance wherein a modulated light signal is transmitted from one end to the other end of the distance and is reflected back again to said one end and wherein the phase difference or a function of the phase difference is measured for three different modulation frequencies f_1, f_2 and f_3 between the light signal being transmitted at said one end and the reflected light signal upon arrival back at said one end, wherein the frequency f_1 corresponds to a wavelength in air under normal conditions of ten metres or a multiple of ten metres, wherein either $f_2/f_1=(10^n \pm 1)/10^n$ and $f_3/f_1=(10^m \pm 1)/10^m$ or $f_2/f_1=10^n/(10^n \pm 1)$ and $f_3/f_1=10^m (10^m \pm 1)$, where m is an integer and $n=m+2$, wherein the value of the distance is determined approximately from the phase difference measurements or function of phase difference measurements at frequencies f_1 and f_2 and is expressed metrically as a multi-digit number of which some digits are relatively of higher orders and the remaining digits are relatively of lower orders, and wherein any error in the relatively lower order digits is recognised and corrected from the phase difference measurement or function of phase difference measurement at frequency f_3.

According to another aspect of the invention there is provided a device for use in measuring a distance according to the method according to the invention, comprising a light source for producing a light beam, a frequency generator adapted and arranged to generate three signals each at a respective one of said frequencies f_1, f_2 and f_3, such that each of the frequencies is stable, a modulator connected to the frequency generator and adapted and arranged to modulate the light beam at each of the frequencies f_1, f_2 and f_3, a beam splitter to split the light beam into a first sub-beam for transmission and reflection back over said distance and into a second sub-beam for use as a reference, a reflector for reflecting said first sub-beam at said other end of said distance, a variable light path or variable optical delay line, and a phase-sensitive detector unit adapted to compare the phases of said first and second sub-beams after said first sub-beam has been transmitted and reflected back over said distance and after one of the sub-beams has passed through said variable light path or variable optical delay line, the phase-sensitive detector having a meter with a zero position in the middle thereof.

The invention will be described by way of example with reference to the accompanying drawings, wherein:—

Figure 1 is a block diagram of a device in accordance with the present invention;

Figure 2 shows a part of the device of Figure 1; and

Figure 3 shows another part of the device of Figure 1.

In carrying the invention into effect according to one convenient modeb y way of example, Figure 1 shows an electro-optical device in which a beam of light emitted by a source 1 travels through a modulator 3 driven by an oscillator 2, supplying three signals

at stable frequencies f_1, f_2 and f_3 fixed by a common quartz oscillator, frequency f_1 corresponding to a wavelength in air under normal conditions of ten metres or a multiple of ten metres, frequencies f_1 and f_3 being such that either $f_2/f_1=(10^n\pm1)/10^n$ and $f_3/f_1=(10^m\pm1)/10^m$ or $f_2/f_1=10^n/(10^n\pm1)$ and $f_3/f_1=10^m/(10^m\pm1)$, where m is an integer and $n=m+2$. The beam is split into two parts by a beam divider 4. The first part reaches the remote reflector 5 and returns to the detector unit 7, while the other part also arrives at the unit 7 through a variable light path 6 (optical delay line). The light beam travelling along the path 4—5—7 contains information concerning the distance to be measured in the form of phase delay (this constituting a measuring-signal channel) while the other travelling along path 4—6—7 represents a reference base (constituting a reference-signal channel). Both the light signals are transformed into electrical signals by two photoelectric transducers (photomultipliers, photodiodes or phototransistors) and are compared in a phase-measuring unit 8. The phase difference between both signals is measured by bringing the difference to 90° or to 270° by the delay line 6. This situation is indicated by ammeter 9 which has the zero position in the middle. To facilitate phase measurement the oscillator 2 modulates the detector 7 so that at the output of the latter there appears an intermediate frequency of unchanged phase content (mixing).

The power-consuming units are fed by a power supply unit 10.

The following features are included in the device.

1) Light source. A gas laser is employed for the light source. Of the well known advantages of lasers the following are emphasised:

a) the monochromatic nature of the laser beam facilitates the use of high reflection dielectric mirrors and small bandwidth interference filters in the optical system.

b) the small aperture of the beam makes the coaxial construction of the emitting and receiving optics possible with low loss values maintained.

2) High frequency oscillator. The accuracy of the device depends to a great extent on the stability over a period of time of modulation frequencies and on the steadiness of their relation. For this reason, such crystal-oscillator and circuits are used which derive all the measuring and mixing frequencies from the frequency of one crystal by means of dividing and mixing. A further advantage of this solution is the possibility of using the same frequency alternately for the modulator and the detector. This brings forth considerable simplification in circuitry.

3) Light modulator. Known devices that have been used industrially have so far, used Kerr-cells for light modulators. It is preferred to use one variant of the well known electro-optical Pockels-cell for this purpose. Thereby, besides avoiding the disadvantages of the Kerr-cell, the following advantages are also obtained:

a) the optimum operating point of the modulator may be adjusted by optical-polarization means for instance through a so-called $\lambda/4$ plate. This is simple and requires no electrical consumption:

b) in consequence of the linear character of the Pockels-effect less distortions arise and the measurement accuracy is increased:

c) by rotating the $\lambda/4$ plate through 90° it is possible to change the phase of the modulation by 180°.

4) Light beam divider. The small diameter of the laser beam enables a birefringent crystal—preferably calcite or sodium nitrate—to serve both as the analyser and as the light beam divider. In contrast to conventional polar filters, not only does this achieve lower light losses, but the reference light signal need not be generated at the expense of the measuring signal, bcause of one beam being always extinguished in conventional analysers.

Figure 2 illustrates one form of light modulator and beam divider. The linear polarized light beam of a gas laser I passes through a $\lambda/4$ plate 11, which can be rotated in its own plane, and then through two electro-optical crystals 12 and 13, preferably ADP or KDP and then through transparent electrodes 14, deposited on the surfaces of said crystals, and then further through an analyser-beam divider 15, which is formed out of a birefringent crystal — preferably sodium nitrate-crystal, whose optical axis lies in the plane of the drawing (dotted line). The crystals 12, 13 and 15 are also rotatable about an axis lying in the plane of the drawing. The output signal of the high frequency oscillator arrives through the terminals 16 to the electrodes 14.

The principle of operation of the device is as follows: The crystals 12 and 13 are uniaxial when no signal exists, their optical axis being parallel with the propagation of the light beam. In consequence of the electrical field introduced by the signal, the crystals become birefringent also in the direction of their former optical axis. The birefringence of the $\lambda/4$ plate 11 and of the crystals 12 and 13, causes optical phase delay between the two orthogonally polarized components travelling through them and so in the crystal 15, in which they propagate in different directions, interference arises. For this reason both split beams become modulated in amplitude. It can be shown that the two beams Io and Ie are of opposite phases, that their intensities are equal, and that their sum, apart from transmission losses, is equal to the intensity

of the input beam I. The two divided beams are used for measuring and reference signals, respectively.

5) Optical delay line. As mentioned above, the device provides a variable light path for measuring phase differences and further an optical delay line. This is arranged, for instance, in the reference signal channel 4—6—7 and performs an accurate measurable adjustment of the phase difference between the light signals to 90° or 270°.

The main defects of the electrical phase shifters applied so far in known devices are the low resolving power and the poor stability of their electrical components. This fact reduces the accuracy of the instruments and increases the time consumption of the measuring process because these phase shifters must be calibrated by a constant optical line after any reading.

Attempts to employ variable optical paths instead of electrical phase shifters were unsuccesful either on account of complicated constructions (e.g. Swiss Patent No. 301,849) or because they could be applied only at very high frequencies (e.g. German Patent No. 1,031,004). The optical delay line applied here for measuring phase differences makes possible the adjustment and digital readout of the delay with high accuracy, temporal stability and with no dependence on temperature fluctuations

The operation principle of the optical delay line is as follows. Light travels forth and back between two concave mirrors in a predetermined manner and passes a variable number of given steady and digitally readable number of times a given distance between the said mirrors. After leaving the field of said mirrors the light travels further between four flat mirrors or glass prisms, of which two are movable with fine measurement and covers a continuous variable distance, after which the light leaves the delay line.

Figure 3 shows an example of the optical delay line. Both spherical concave mirrors 21 and 22 are arranged coaxially with one another. Their radii of curvature and the angle of incidence of the light beam introduced through the mirror 23 are so chosen that the points of incidence of the beam reflected back and forth lie on circles on the surface of the concave mirrors. The output coupling system constituted by the mirrors 24, 25, 26 and 27 provides for the removal of the beam from the delay line, after it has traversed a predetermined number of distances between mirrors 21 and 22 (coarse phase shift) and after passing two continuously variable distances between the mirrors 24—27 (fine phase shift). For this purpose, by means of disc 29 equipped with graduations, the mirrors 24 and 25 can be rotated together around the axis of the concave mirrors and in steps of fixed angles so that the mirror 24 always stops at a point of incidence on the mirror 21 and thereby deflects the light towards mirrors 25—26—27, while the mirrors 26 and 27 can be moved along the axis of the mirrors 21 and 22 and their movement is digitally readable on the dial 30, which moves the mirrors 26 and 27 by means of a screw, not shown. By these means, the light beam after passing twice the distance 25—26 leaves the delay line. The resulting phase-shift, apart from constant distances, such as the light path 24—25, is constituted then by the sum of the readings from the disc 29 and from the dial 30.

The optical delay line 6 is shown in the reference-signal channel, but it could be in the measuring-signal channel.

6) Detector unit. Its function is to receive the arriving weak light signals, to transform them into electrical signals, to amplify them without altering their phase and to prepare them, by means of modulation or rectification for phase measurement.

Three forms of detection may be used namely:

a) a photomultiplier in such an arrangement that its cathode circuit is modulated so that a difference frequency appears in the anode current. This has the following advantages:

(i) the same frequency serves once for the modulation of light and later for the modulation of the detector and *vice versa*. Therefore, the oscillator should produce an essentially lower number of frequencies and so a simplification in circuits and a reduction of sources of error is achieved;

(ii) there is permitted, through a suitable choice of frequencies, a very simple and quick measuring method.

b) Synchronous demodulation may be used. With a conventional synchronous demodulator using a Kerr cell, one can increase the otherwise low accuracy through a periodic alternating of the bias on the Kerr-cell (for instance according to the Swedish Patent No. 175,451). To avoid the difficulties inherent in this, the device may use a synchronous demodulation through a crystal-modulator according to feature 3. Here the photomultiplier operates only as a sensitive element for light intensity without performing the role of the detector.

The replacement of said bias-alternating by polarizing optical means is possible. It can be shown that the rotation either of the $\lambda/4$ plate 12 or of the beam-divider 15 through 90° performs the same phase changes at 180°, as the alternating of the bias of the Kerr-cell.

c) In a third form of the detector unit photomultipliers are replaced by photo-

diodes or phototransistors. This results in the following advantages: a decrease in dimensions, weight, voltage and power requirements, the avoidance of the so-called transit time effects in photomultipliers, and finally better spectral response.

The evaluation of the measurement results obtained with conventional electro-optical devices includes complicated computations, whose accomplishment in the field is sometimes impossible.

These disadvantages may be avoided and the accuracy of the measurement improved due to the following:—

1) Higher accuracy ensured by the optical delay line 6.
2) Use of only two, so-called, measuring frequencies and a third, so-called, correction frequency, as explained hereinafter in relation to a numerical example.
3) Measurement of the phase differences in such units of length, that the distance can be computed quickly from the combination of three phase differences by means of addition and subtraction of simple numbers.

The following relationships can be derived from the known theory of electro-optical devices:

$$D=N_1\frac{\lambda_1}{4}+L_1=N_2\frac{\lambda_2}{4}+L_2=N_3\frac{\lambda_3}{4}+L_3 \quad (1)$$

$$\lambda_1=\frac{c}{f_1},\quad \lambda_2=\frac{c}{f_2},\quad \lambda_3=\frac{c}{f_3} \quad (2)$$

$$|\Delta D|<\frac{1}{4}\Lambda_{12}=\frac{1}{4}\lambda_1\frac{f_1}{f_1-f_2} \quad (3)$$

$$N_1=(N_1-N_2)\frac{f_1}{f_1-f_2}+\frac{L_1-L_2}{\frac{\lambda_1}{4}}\,\frac{f_2}{f_1-f_2} \quad (4)$$

$$D=(N_1-N_3)\frac{1}{4}\Lambda_{13}+\left(\frac{L_1}{\frac{\lambda_1}{4}}-\frac{L_3}{\frac{\lambda_3}{4}}\right)\frac{1}{4}\Lambda_{13}=N_{13}\frac{\Delta}{4}\Lambda_{13}+L_{13} \quad (5)$$

$$\Delta(L_1-L_2)<\frac{\lambda_1}{4}\,\frac{f_1-f_2}{f_2} \quad (6)$$

$$\Delta(L_1-L_3)<\frac{\lambda_1}{4}\,\frac{f_1-f_3}{f_3} \quad (7)$$

where

D—is the distance (in metres)

c—is the velocity of light (in m/sec.)

f_1, f_2, f_3—are the measuring frequencies (in c/sec)

N_1, N_2, N_3—are the so-called wavenumbers i.e. the ratios of the distance and of the quarter wavelengths.

λ_1, λ_2, λ_3—are the wave lengths of modulation (in metres)

L_1, L_2, L_3—are the remainder distances, i.e. the phase-differences measured in units of length at the particularly frequencies (in metres)

$|\Delta D|$—is the error, with which the required disance must be known to ensure unambigous measurement

Λ_{12}, Λ_{13}—are the virtual wave lengths corresponding to the difference of the measuring frequencies (in metres)

L_{13}, N_{13}—are the remainder distance and wave number, respectively, corresponding to the wavelength Λ_{13}

$\Delta(L_1-L_3)$, $\Delta(L_1-L_2)$—are the admissible errors of phase measurement (in metres).

Considering the known fact, that one can decide from the relative sense of motion of

the delay line 6 and the instruments 9 whether the wave numbers are odd or even we can transform the measured remainder distances so that the new wave numbers will be even. But the change can be made also so that the new remainder distances of any frequency will be higher, than that of another one. If we substitute for example

$$N_1+1 \text{ instead of } N_1$$

and

$$L_1'=L_1-\frac{\lambda_1}{4} \text{ instead of } L_1$$

thereby the equation (1) remains obviously right. On the basis of the above considerations we can suppose that all wave numbers are even and that

$$L_1>L_2 \text{ and } L_1>L_3$$

Indeed, with the proper choice of the frequency-ratios, if

$$\left.\begin{array}{l} \dfrac{f_2}{f_1}=\dfrac{10^n\pm1}{10^n} \text{ and } \dfrac{f_3}{f_1}=\dfrac{10^m\pm1}{10^m} \\ \text{or} \\ \dfrac{f_2}{f_1}=\dfrac{10^n}{10^n\pm1} \text{ and } \dfrac{f_3}{f_1}=\dfrac{10^m}{10^m\pm1} \end{array}\right\} \quad (8)$$

it results from the equations (1) and (4) with the values for example: $n=3$ $m=1$

$$D \cong 1000\ (L_1-L_2)+L_1 \qquad (4a)$$

and

$$L_{13}=10\ (L_1-L_3)+L_3 \qquad (5a)$$

Equation (4a) shows that the value of the measured distance can indeed be computed by simple addition and subtraction of the remainder distances, but because an error of e.g. 10 mm committed in measuring L_1 and L_2 in the amount of D must be multiplied by 1000 and so an error of 10 m, is resulted, care should be taken in the recognition and correction of the latter. The measurement at the frequency f_3 according to equation (5a) may serve for this purpose.

The method of correction can simply be explained in connection with a numerical example.

We choose for example the frequencies with the exponents in equations (8) so, that:

$$f_1=15.10^6 \text{ c/sec}$$

$$m=1$$

$$n=3$$

being thereby

$$\frac{\lambda_1}{4}=5.\text{—m} \qquad \frac{\lambda_2}{4}=5.005 \text{ m} \qquad \frac{\lambda_3}{4}=5.555 \text{ m}$$

further

$$1/4\ \Lambda_{12}=5000 \text{ m} \qquad 1/4\ \Lambda_{13}=50 \text{ m}$$

$$\Delta\,(L_1-L_2)<5 \text{ mm},\ \Delta\,(L_1-L_3)<500 \text{ mm}$$

and supposing even wave numbers: N_2, N_1 and $N_{13}=N_1-N_3$

$$N_{13}\,\frac{1}{4}\,\Lambda_{13}=i.100 \text{ m}$$

where i is an integer. Now by comparing equations (5) and (5a) the value

$$L_{13}=10\ (L_1-L_3)+L_3$$

obviously gives the remainder of D above 100 m and the accuracy 3 is also sufficient provided that the error in measuring L_1 and L_3 does not exceed 500 mm. However, as the first two digits of the remainder must agree with the last two digits computed from equation (a), the error in measuring L_1 and L_2 can be determined comparing the two digits and also the false values of latter can be corrected. This can be done, for example, by changing L_1 and L_2 until the compared digits reach agreement.

Applying this example to an actual distance. Suppose that the following phase differences were measured:

$$L_1=6.532 \text{ m}$$

$$L_2=4.880 \text{ m}$$

$$L_3=2.318 \text{ m}$$

and the relative direction of motion of the delay line 6 and instrument 9, was such, that no transformation of the values was necessary and all wave numbers are even.

The procedure of evaluation is the following:

a) from equation (4a), as a first approximation is computed:

$$D=(6.532-4.880)\ 1000=1652 \text{ m}$$

b) however, from equation (5a), with higher accuracy the last two digits are calculated.

$$L_{13}=10\ (6.532-2.318)+2.3=44$$

c) because the accuracy according to (b) exceeds that according to (a) the two last digits must be 44 and not 52. From this it can be stated that at the measur-

ing of L_1 and L_2 there was an error of total: $52-44=8$ mm. For the correction L_1 is decreased by 4 mm and L_2 is increased by 4 mm, thereby

$$L_1'=L_1-0.004=6.528 \text{ m}$$

$$L_2'=L_2+0.004=4.884 \text{ m}$$

are obtained.

d) from these values the required distance can now be computed according to equation (4a). It can also be taken into consideration that the first term in said equation is the same, as the first term in equation (1) which in turn provides a round value of 10 m, since L_1 is even and $\frac{\lambda 1}{4}=5$ m. Thereby there is a further correction possibility by rounding to the nearest ten metres

$$D\cong 1000\ (L_1'-L_2')=1000\ (6.528-4.884)=\cong 1644=1640 \text{ m.}$$

Finally for the accurate value:

$$D=1000\ (L_1'+L_2')+L_1'=1640+6.528=1646.528 \text{ m}$$

is obtained.

It can be also derived more simply in the following manner, quite mechanically, by obtaining the first two digits from equation (4a), the third digit from equation (5a) and the last digits from L_1' (provided of course that the corrections according to the point (c) have been performed).

The successful application of this method requires the following preliminary conditions:

1) a minimal accuracy of phase measurement, limited by the inequalities (6) and (7). This will be ensured by the optical delay line 6.
2) The exact frequency-ratios determined by equations (8). This will be attained through those said circuits (point A/2) which derive all frequencies from that of one crystal;
3) such choice of the so-called basic frequency f_1 that the wavelength λ_1 is 10 m or its multiple in air of normal condition.

For the evaluation of the measured distance, it is necessary that $L_1>L_2$. It may be shown that the wave numbers should be both odd or both even. Otherwise, transformation by substituting N_1+1 for N_1 and substituting $L_1'=L_1-\frac{\lambda}{4}$, as described above, is necessary.

WHAT WE CLAIM IS:—

1. A method of measuring a distance wherein a modulated light signal is transmitted from one end to the other end of the distance and is reflected back again to said one end and wherein the phase difference or a function of the phase difference is measured for three different modulation frequencies f_1, f_2 and f_3 between the light signal being transmitted at said one end and the reflected light signal upon arrival back at said one end, wherein the frequency f_1 corresponds to a wavelength in air under normal conditions of ten metres or a multiple of ten metres, wherein either $f_2/f_1=(10^n\pm 1)/10^n$ and $f_3/f_1=(10^m\pm 1)/10^m$ or $f_2/f_1=10^n/(10^n\pm 1)$ and $f_3/f_1=10^m/(10^m\pm 1)$, where m is an integer and $n=m+2$, wherein the value of the distance is determined approximately from the phase difference measurements or function of phase difference measurements at frequencies f_1 and f_2 and is expressed metrically as a multi-digit number of which some digits are relatively of higher orders and the remaining digits are relatively of lower orders, and wherein any error in the relatively lower order digits is recognised and corrected from the phase difference measurement or function of phase difference measurement at frequency f_3.

2. A device for use in measuring a distance according to a method as claimed in claim 1, comprising a light source for producing a light beam, a frequency generator adapted and arranged to generate three signals each at a respective one of said frequencies f_1, f_2 and f_3, such that each of the frequencies is stable, a modulator connected to the frequency generator and adapted and arranged to modulate the light beam at each of the frequencies f_1, f_2 and f_3, a beam splitter to split the light beam into a first sub-beam for transmission and reflection back over said distance and into a second sub-beam for use as a reference, a reflector for reflecting said first sub-beam at said other end of said distance, a variable light path or variable optical delay line, and a phase-sensitive detector unit adapted to compare the phases of said first and second sub-beams after said first sub-beam has been transmitted and reflected back over said distance and after one of the sub-beams has passed through said variable light path or variable optical delay line, the phase-sensitive detector having a meter with a zero position in the middle thereof.

3. A device as claimed in claim 2, wherein the frequency generator comprises a crystal oscillator and means for generating the three signals all from said crystal oscillator.

4. A device as claimed in claim 2 or 3, wherein the light source is adapted to produce monochromatic linearly polarised light and wherein light paths in the device are *via* high reflectivity.

5. A device as claimed in any one of claims 2 to 4, wherein the modulator comprises electro-optical crystals and wherein a λ4 plate is arranged before the said crystals in order to adjust the operating point of the modulator and can be rotated about an axis parallel to the propagation of light, said beam splitter comprising a birefringent plate arranged behind said crystals so that it performs at the same time the role of an analyzer.

6. A device as claimed in any one of claims 2 to 5, wherein the variable light path or optical delay line defines an optical path which is variable both in steps and continuously, wherein there are provided two coaxial spherical concave mirrors with the radii of curvature of said mirrors and the angle of incidence of the introduced light beam being so chosen that the points of incidence of the light rays reflected back and forth between the said mirrors are arranged on circles on the surface of the said mirrors, and wherein there is provided an input-coupling mirror, and a system of four output coupling mirrors of which two mirrors can rotate together about the axis of said concave mirrors in steps, the third and fourth of said mirrors being movable along the axis of the said concave mirrors together and continuously in a measurable manner.

7. A device according to claim 6, wherein all said mirrors are formed with high reflectivity dielectric layers.

8. A device according to any one of claims 2 to 7, wherein photodiodes or phototransistors are applied for the purpose of detecting, amplifying and mixing of the light signals.

9. A device for measuring a distance substantially as described with reference to the accompanying drawings.

MARKS & CLERK,
Chartered Patent Agents,
Agents for the Applicant(s).

Printed for Her Majesty's Stationery Office, by the Courier Press, Leamington Spa, 1972.
Published by The Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

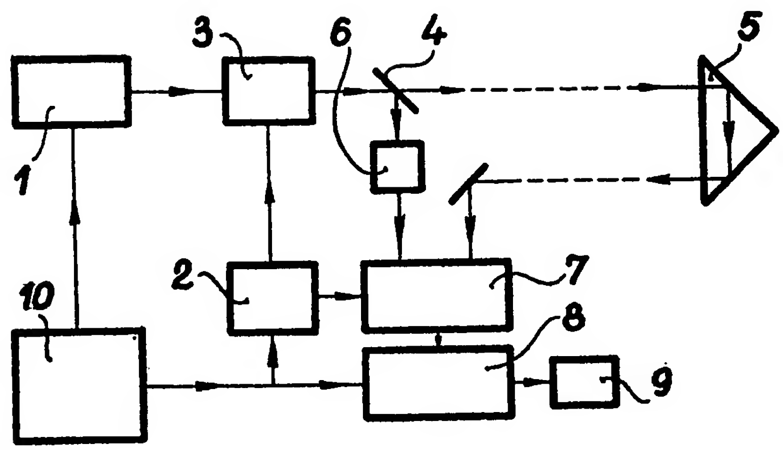

Fig. 1

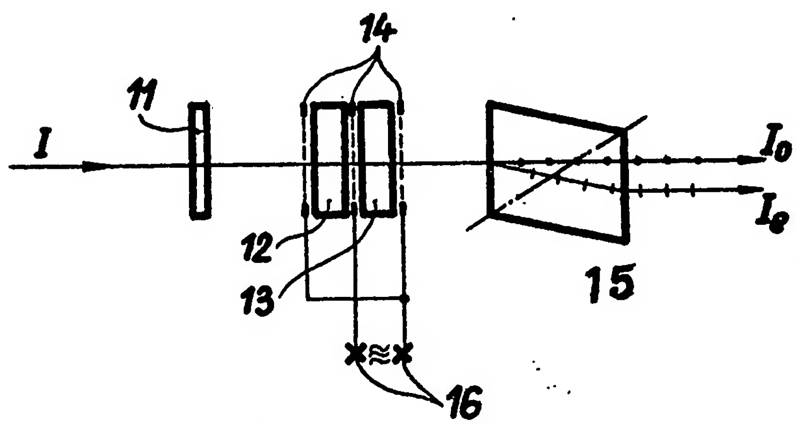

Fig. 2

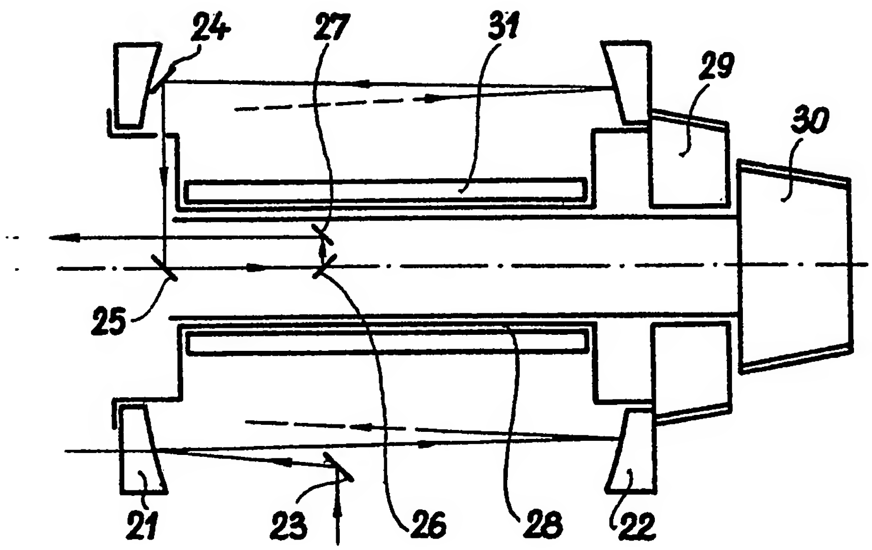

Fig. 3